A RAND NOTE

LHX Mission Analysis Using MOSF SUN Terrain
Procedures: An Overview of System Logic

Albert L. Zobrist, Luis J. Marcelino

May 1989

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The mission analysis element of the RAND
LHX (Light Helicopter Experimental) study
is concerned with comparative analysis of
helicopter/tilt rotor configurations in a
mission context. Complex mission contexts
are simulated with the standard JANUS
system. This Note describes a
RAND-developed system that supports and
enhances the JANUS results by applying
higher data resolution and greater
engineering detail to selected parts of the
JANUS cases.

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PREFACE AND OVERVIEW

This Note covers an element of the Arroyo Center project entitled the Alternative Army Airframes Analysis; also referred to as the LHX study. The study objective was to recommend to the Army an acquisition strategy for the development of an Army aircraft that can best meet the Army's tactical aviation requirement, given the current state-of-the-art of the various technologies and their ability to perform the various missions. Final study results and conclusions were briefed to representatives of the U.S. Army and OSD on November 10, 1987.

This project was sponsored jointly by the Honorable Richard Godwin, Under Secretary of Defense for Acquisition, and the Honorable James Ambrose, Under Secretary of the Army. It was conducted within the Force Development and Employment Program of the Arroyo Center and coordinated with a parallel study by the Institute for Defense Analyses (IDA).

Other Notes and Reports documenting component analyses of the study are:

R-3625-A, *Design, Performance, and Cost of Alternative LHX Configurations*, G. K. Smith, G. Acker, J. H. Bigelow, D. Dreyfuss, S. Laforge, R. Pei, S. Resetar, and R. Petruschell (Competition Sensitive), November 1988.

R-3623-A, *The Army Alternative Airframes Analysis: Overview Report (U)*, S. Drezner, B. Rostker, E. Gritton, G. Smith, and M. Callero (Secret/Competition Sensitive). To be published.

R-3621-A, *Engineering Survivability Analysis of LHX Aircraft Alternatives (U)*, E. Gritton, H. Bailey, C. Crain, L. Mundie, H. Ory (S/CSI/NOFORN/WN). To be published.

R-3617-A, *LHX Helicopter and Tilt Rotor Flight Simulator Experiment*, C. T. Veit, M. Callero, and B. J. Rose. To be published.

R-3616-A, *Small Unit Operational Performance of LHX Variants (U)*, M. Callero, J. Bondanella, D. Norton, and A. Zobrist (Secret). To be published.

N-2725-A, *LHX Communication Issues (U)*, E. Cesar, H. Ory, and M. Schaffer (Secret). To be published.

N-2724-A, *LHX Armament (U)*, M. Schaffer and W. Benson (Secret). To be published.

N-2721-A, *LHX Mission Equipment Package Tradeoffs*, M. Schaffer and H. Ory (Competition Sensitive). To be published.

N-2720-A, *Reactive Threat to LHX (U)*, J. Hiland, L. Mundie, and C. Crain (Secret). To be published.

N-2719-A, *Automatic Target Recognition for LHX*, H. Bailey, H. Ory, and M. Schaffer, January 1989.

N-2718-A, *Reducing Risks Associated with Developing the LHX Mission Equipment Package*, M. Berman, D. McIver, B. Orvis, M. Robbins, and R. Ruth, January 1989.

N-2708-A, *Pilot Workload Reduction and Mission Equipment Package Utilization for LHX*, D. Hartley. To be published.

THE ARROYO CENTER

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Army Regulation 5-21 contains basic policy for the conduct of the Arroyo Center. The Army provides continuing guidance and oversight through the Arroyo Center Policy Committee, which is co-chaired by the Vice Chief of Staff and by the Assistant Secretary for Research, Development, and Acquisition. Arroyo Center work is performed under contract MDA903-86-C-0059.

The Arroyo Center is housed in RAND's Army Research Division. The RAND Corporation is a private, nonprofit institution that conducts analytic research on a wide range of public policy matters affecting the nation's security and welfare.

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**THE ARMY ALTERNATIVE AIRFRAMES ANALYSIS:
OVERVIEW OF MAJOR FINDINGS AND POLICY
RECOMMENDATIONS[1]**

The Army Alternative Airframes Study, also known as the LHX study, set out to assess the capabilities of various aircraft alternatives to perform the Army's aerial attack and scout missions. Although airframes based on more advanced technologies were considered, the study focused primarily on three generic alternatives: an advanced conventional helicopter, a tilt rotor, and an upgraded Apache.

Our primary recommendation is that the Army develop and procure a new advanced conventional helicopter rather than a tactical tilt rotor or an Apache upgraded to meet the LHX requirements. This choice is supported by all aspects of our study: the engineering and flight simulator analyses; the cost analyses; the force-on-force analyses of unit- and theater-level operational performance; and the analyses of factors beyond cost and performance.

However, we conclude that the Army's emphasis should not be on lightness per se, but on the features that will be incorporated into a new "Advanced Helicopter System." Based upon our analysis, we have concluded that a new helicopter weighing about 12,000 lb will be necessary to fully accomplish the SCAT missions designed for the LHX. Furthermore, we found that lower weight is not a very good surrogate for lower cost or higher survivability. To design a truly light helicopter—on the order of 10,000 lb—requires giving up mission-essential functions with little cost savings. For example, a 13 percent savings in weight from the 12,000 lb helicopter translates into only a 3 percent savings in total incremental life cycle costs. **Rather than on weight, the design focus should be on mission performance, survivability, cost (i.e., force size for a fixed budget), and robustness.**

We refer to this new aircraft as a "helicopter system" to emphasize how greatly its cost-effectiveness depends on highly advanced subsystems, in particular the Mission Equipment Package (MEP) and, secondarily, the armament. This observation is important regardless of which airframe the Army selects for the LHX SCAT role.

The successful development of the MEP is critical to achieving the program's planned performance and cost goals. In particular, the reliability and maintainability (R&M) of the MEP will heavily influence LHX O&S costs. Currently the Army expects the LHX

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[1]This is a summary of the major findings and policy recommendations of the Army Alternative Airframes Analysis as a whole; it is provided here as a context for the technical description of the software system SUN Terrain Procedures provided in this Note.

to experience 80 percent fewer removals than the Apache, a reduction that, if achievable, would result in a projected $6 billion savings in spares and manpower over the life cycle of the helicopter. However, the MEP involves a significant technological advance, and the associated technical risk must be carefully managed. Fortunately, the Army is in a position to capitalize on Air Force and RAND experience with advanced avionics. This experience demonstrates that integrated digital subsystems have complex failure modes which require time to understand in the operational environment. Once they are understood, it is within the state-of-the-art to write the appropriate software for fault isolation and detection.

The Army can realize its goals for MEP performance and supportability by carefully maturing the subsystem through development and early fielding. The approach involves the intensive, phased collection of detailed engineering data and includes special R&M-related testing during development. The maturation process requires data from about 25,000 flying hours, based on the helicopter's performance in its actual operating and maintenance environments. While the MEP's R&M is being matured, special support structures may be needed to boost performance. This approach implies a low rate early production to avoid the high cost of retrofitting a large portion of the force. We estimate the total cost of such a program to be $120 to 370 million—a small price to pay for the projected savings.

The armament currently planned for the Advanced Helicopter System (AHS) will likely require upgrading early in the aircraft's field life. The AHS should have the potential to carry fire-and-forget missiles; in addition to the Airborne Adverse Weather Weapons System (AAWWS), we suggest a **Combined Arms Multipurpose Missile System (CAMMS)** that has capability against both ground armor and remasked helicopters.

Finally, **the AHS must be robust enough to play in the counter/countermeasure game** that will begin as it enters the field. We recommend that study of potential reactive threats should begin now.

Our analyses of unit-level operational performance indicate that reduced radar signatures are less important than we had expected, at least in the close-in battle. A robustness in this area is still required for several reasons, including the ability of the threat to adapt. The Army should begin with as "clean" a design as possible, and the design philosophy for the AHS should include a strategy to incorporate passive signature reduction measures initially since including them later in the life of the system would be much more difficult.

In addition, we recommend that the Army improve the survivability of the
Apache through a reduced signature prototype program. Greater survivability would
increase the Apache's mission performance and flexibility. If the program demonstrates the
feasibility and utility of reducing the Apache's signature, and the Army decides to retrofit
accordingly, it should also reassess the planned mix of LHX (i.e., AHS) and Apache.

We should note, however, that for the LHX role itself we prefer a new advanced
conventional helicopter over even an upgraded Apache with reduced signature. A new
helicopter will leave the Army better positioned to evolve its tactical aviation forces after the
year 2000.

We further recommend that the Army should develop an austere prototype of
an operational configured tilt rotor to validate technical performance and to enable
development of employment tactics that would exploit the special characteristics of
that design. Our analyses confirm the tilt rotor's advantages in speed and range and reveal
some intriguing maneuverability capabilities. Our analyses did not show that the speed
provides significant overall operational advantages. It might permit a modest increase in
sortie production and appears to increase survivability for certain missions. Prototypes will
enable the Army to explore the tilt rotor's suitability for specialized missions (such as air-
to-air and troop insertion), leaving this option open for the future.

Finally, we believe that the decision concerning a new utility helicopter can wait.
Either the tilt rotor or the AHS could spin off a utility version. The choice of utility
helicopter, therefore, should not be a factor in the LHX SCAT decision.

SUMMARY

The need to evaluate Army attack helicopters in a mission context which allows slight differences in physical characteristics to be measured in terms of capability and mission effectiveness motivated the development of software called the SUN Terrain Procedures (STP). This new modelling and analysis system fills a niche within a hierarchy of models used to analyze various levels of engineering accuracy and simulation detail. Engineering studies use high accuracy to compare helicopters in single maneuvers (e.g., a turn or climb) or in a short sequence of maneuvers. The mission context adds important variables such as spatial distribution of defenses, terrain, and targets. However, these mission studies must meet with acceptance and understanding through the use of standard simulators such as the JANUS system. The ability to bridge the gap between these two approaches with a locally developed system was made possible by the availability of a number of technical elements within the RAND Military Operations Simulation Facility (MOSF). These elements include:

1. Powerful 32-bit microcomputers (SUN and VAX)
2. Large memories (4 to 16 megabyte)
3. Capable graphics for image and vector data
4. The JANUS system (colocated with MOSF)
5. Geographic data supporting the study areas
6. A geographic information system to prepare geographic data
7. Terrain elevation processing including line-of-sight calculation
8. Image processing capability to process terrain data
9. HELCOM flight capability data in computer table form supplied by the LHX project
10. An engineering analysis system

The STP allow the analyst to graphically define and evaluate a flight path over a geographical area, taking into consideration the geographical area's terrain and cultural features, locations of enemy sensors and air defense systems, line of sight, and flight time characteristics associated with each air defense system, determining probabilities of kill and circular area probabilities along the "visible" regions of the aircraft's flight path.

The three phases of STP operation are: (1) preparation of geographic data sets, (2) interactive graphics for flight path entry, and (3) analysis of the path. This Note begins with a system description and then describes the three phases in order. An appendix shows in greater detail how the interactive graphics are used.

ACKNOWLEDGMENTS

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FIGURES

I. INTRODUCTION

The Army community has benefitted greatly from the use of high-resolution graphics-based systems such as JANUS for military simulation and analysis. First developed at Lawrence Livermore Laboratory to analyze tactical nuclear weapons, JANUS has been extensively modified at the Army's TRAC facility at White Sands Missile Range for a much wider range of situations. The Arroyo Center at RAND has created an active JANUS laboratory colocated with the Military Operations Simulation Facility (MOSF) and plans an increasing use of this facility. At the same time, a small effort has begun to create a new system, supplementary to JANUS, that trades full battlefield complexity for greater increases in the resolution that can be applied to engineering details. The system is based on the latest available microprocessor technology, including fast 32-bit CPUs, large memories, and capable graphics. Since the ability to input terrain is a key element of the system, and SUN computers are used, the system has become known as STP, for SUN Terrain Procedures.

The STP system is designed to represent terrain data and culture in graphical display format for user-friendly operator (pilot) interaction and to use an image processing format for greatest resolution and analytic capabilities. It is capable of representing a flight path close to the nap of the earth with a resolution of about a foot vertically and 10 to 25 meters horizontally depending upon the study area scale. The flight path is specified by operator input to a map-like graphics display, and the dynamics of the path are calculated by HELCOM model routines (Ref. 1). Intervisibility between the aircraft and defensive sites can be accurately calculated to yield the space and time windows during which the aircraft is exposed. Subsequent batch runs can analyze the effects of particular weapon types on the flight path. Each of these phases of STP operation will be described in the major sections of this Note.

STP consists of about 65 programs for the manipulation of image, graphics, and tabular data, and an executive system that creates a user-friendly interface to the library of routines. STP can be categorized as a geographic information system with additional engineering analysis capabilities. The main components of STP include: (1) STP executive, (2) image processing routines, (3) polygon file processing routines, (4) table processing routines, and (5) project-specific application routines. These components are described in the next five subsections.

STP EXECUTIVE

The executive for STP is the Transportable Applications Executive (TAE) developed by the NASA Goddard Space Flight Center and Century Computing Inc. Each of the 65 application programs has a simple interface to the TAE executive that defines the parameters that a user might want to set when the program is run. The user is offered four modes of operation.

1. A command list naming the program and the values of named parameters.
2. A tutor mode in which a window pops up with parameter names, descriptions, help options, default values, etc., with command buttons for run, exit, or other types of help.
3. A procedure mode that allows the user to string together any number of commands into a higher level procedure. Procedures can then be treated the same as programs.
4. A menu mode that allows the user to find a program or procedure.

Some examples of TAE procedures are given in later sections. Because TAE is available on VMS or UNIX, is written in C language, and is itself modular, the whole system is portable and allows portability of applications. TAE facilitates incremental growth of the application routines, decreases maintenance costs, provides system services, and allows portability. TAE also comes with complete on-line documentation, has a complete field history, and is independent of discipline, project, or data type, hence it is very reliable. TAE provides an excellent user-friendly interface that insulates the user from the host operating system, provides a congenial and consistent environment, and has a parameter prompting feature. TAE provides long-term support with a support office, phone-in service, a full library of on-line and paper documentation, a newsletter, and a biennial user's conference.

IMAGE PROCESSING ROUTINES

An image is a large matrix of cells that can represent two-dimensional spatial data. For example, elevation data are represented by projecting an area of the earth onto the cellular matrix and placing the elevation of the terrain (as a number) into each corresponding cell. Because these image data sets are large, an image processing system is useful for retrieving, manipulating, and displaying them. Special functions such as line-of-sight calculation are then added to the menu.

A standard image format is defined that requires a label giving image size, type, and history. Supported types include character, short integer, integer, floating point, double precision, and complex. The presence of a label relieves the user from having to specify the data size over and over when a long procedure is performed. Large image processing is supported. Programmers are requested to allow for a 10000 x 10000 image size in all programs except where that size does not make sense. The programs and their functions are:

- IMLOG - create an image from external data in binary or character format
- DTEDLOG - create an image from DMA DTED (Defense Mapping Agency Digital Terrain Elevation Data)
- IMCOPY - copy all or a subwindow of an image
- IMLIST - print part of an image
- IMARITH - apply an arithmetic function to (up to) five images
- IMSIZE - resample an image to new pixel size
- IMFFT - compute two-dimensional fast Fourier transform of an image
- IMAPGEN - substitute table values in an image (choroplethic mapper)
- IMSHADE - compute shading for terrain data for a color graphic display
- CONTOUR - compute contours for image terrain data
- FILL - fill polygon contours in an image
- MOSAIC - join adjacent images into a larger image
- OVERLAY - polygon overlay in image format (yields a table)
- GETZVAL - read image values at locations given in a table
- PUTZVAL - put table values into an image at locations from the table
- LOS - compute an image of line of sight for a terrain image (size limited)
- LOSANG - compute an image for angle of depression or glance angle to terrain

POLYGON FILE PROCESSING ROUTINES

Polygon files can contain points, lines, and area boundaries in short integer, integer, floating, or double precision formats. Short labels are attached to all items to aid user processing.

- POLYGEN - create a polyfile from external data in character format

- GDRLOG - create a polyfile from external data in the local graphics format
- TAB2POLY - create a polyfile from data in table format
- GDROUT - write polyfile in to the local graphics format
- POLY2TAB - write polyfile to table format
- POLYLIST - print parts of a polyfile
- DFADLOG - convert DMA DFAD (Digital Feature Area Data) to a polyfile
- METRXLOG - convert digitized data from METREX INC. to a polyfile
- POLYCAT - concatenate two polyfiles
- POLYREG - linear transform of a polyfile containing map data
- POLYMAP - map transformation of a polyfile. This routine also can be used in an interactive mode to make forward and inverse transformations on 20 commonly used map transformations
- POLYSEED - create a file that identifies polygons in DMA DFAD
- POLYTHIN - cull points in a line file maintaining requested accuracy
- POLYTRI - triangulate a point data set for surface fitting
- POLYSCRB - scribe a polyfile into an image

TABLE PROCESSING ROUTINES

Tables are simple flat files of up to a hundred columns and 200000 records. Columns can contain character (variable length), short integer, integer, floating point, or double precision data. The file contains a data dictionary. These routines constitute a complete data management capability for engineering type applications. Typically, the records trace the path of an aircraft, so it is strongly desired to use the sequence of records in most of the calculations. Also, the arithmetic capabilities are heavily used. These characteristics of engineering applications rule out the use of a relational system; however, the convenience of a relational system is kept available by two routines that transfer a table to the Ingres (c) relational database system used at RAND. Because of the limited functionality of this system and because of the TAE interface, this system is very fast and very easy to use.

- DEFTABLE - define a table and its field formats
- ACOPIN - create a table from external data in character format

- ICOPIN - create a table from an Ingres (c) table
- ACOPOUT - write selected parts of a table to character format
- ICOPOUT - write selected parts of a table to an Ingres table
- REPORT - print selected parts of a table with headings
- SORT - sort a table
- RETRIEVE - retrieve a new table from a table
- ARITH - apply an arithmetic function to rows or columns of a table
- JOIN - join values from a secondary table into a table using keys
- JOIN2 - join two tables horizontally, vertically, or cross-product
- AGGRG - aggregate columns of a table according to a control column
- AGGRG2 - aggregate and collapse the table vertically
- PPLOS - compute line of sight in terrain data into a table. The table contains the desired map coordinates and elevations.

PROJECT SPECIFIC APPLICATION ROUTINES

The STP system and the TAE provide an excellent environment for the development of application routines. Because a user interface, system services, documentation aids, and other data handling routines are already in place, the programmer can usually concentrate on the increments of technology needed for his application. Even faster development occurs when tasks can be performed by a procedure — a combination of the standard routines above. Procedures benefit from decreased debugging time since the standard routines are debugged by heavy use in multiple projects. Only the LHX project routines and procedures are listed here. Of the routines below, only FP is a program, the others are user-defined procedures.

- FP - trace a flight path in position, elevation, and velocity through a map-like color graphics display of terrain and culture. A flight dynamics routine, HELCOM, checks for path feasibility and a magnifier window checks for ground clearance. Radars or other sensors and their areas of visibility can be displayed.
- LHXELV - prepare an elevation data set combining DMA DTED terrain data and DMA DFAD culture data (these data sets are described in Sec. II). The user can specify a formula to give random variations in tree density and height.

- **LHXFPPREP** - prepare the color graphic map utilizing a shading technique for the elevation data and color overlays for the culture.
- **LHXW** - calculate window exposure for a flight path, a terrain data set, and a set of defensive sites
- **LHXWREP** - present statistical summaries of the results of procedure LHXW.

II. STP DATA PREPARATION PROCEDURES

One of the features of STP is the rapid conversion of standard geographic files to the internal format of the STP analysis modules. This allows a new study area to be prepared from scratch in about one day so long as the standard files are available. The standard files used in this study were:

1. DMA Digital Terrain Elevation Data (DTED) - These data are produced by stereo photogrammetry and associated data operations and gives terrain elevation at a rectangular grid of points for a spacing of three seconds of arc in latitude and three seconds of arc in longitude. Above 50 degrees latitude, the longitudinal spacing becomes six seconds of arc. Thus, the spacing usually falls between 90 and 120 meters per spacing. The elevation value is given as an integer and is in meters above sea level. More information on the sea level datum and horizontal and vertical accuracy can be found in Ref. 2.

2. DMA Digital Feature Analysis Data (DFAD) - These data are produced by digitization, manual or line-following, from maps and aerial photography. Certain defined land cover types and objects are given as points, lines, or polygons. The points are specified in latitude-longitude, and lines and polygons are specified as chain codes of latitude-longitude points. The polygons are closed by repeating the first point as a last point. Polygons inside of polygons are allowed, and the land cover at a point is determined by the innermost polygon containing it. A DFAD file will have a quadrilateral as its outermost polygon. The polygons are numbered sequentially and referenced to an associated table giving type code (which are numbers giving the land cover type, as defined in Ref. 2), typical height, etc. Thus, for an area of trees, one can read the typical height out of the associated table. Fig. 1 diagrams the DTED and DFAD data sets illustrating their fundamental differences in computer representation.

3. HELCOM Flight Capability Tables - Given aircraft weight, loading, elevation above sea level, and other parameters, the program HELCOM2 will output tables of acceleration capabilities at 10 knot velocity intervals. These can then be used to derive standard maneuvers for analysis. For STP, the identical tables are used for derivation of the maneuvers needed to piece together a mission flight path in a stepwise fashion.
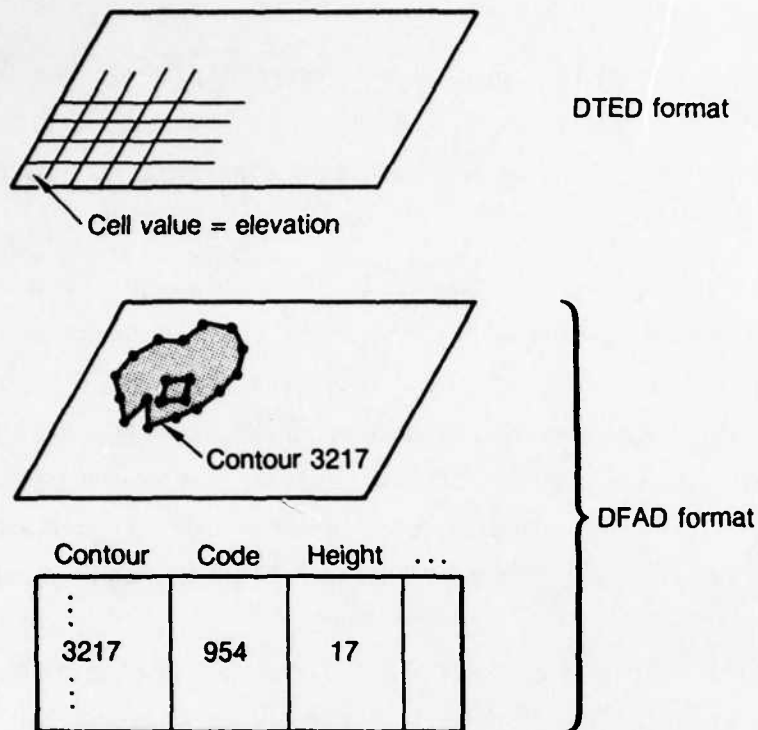
Fig. 1—Computer structure of DTED and DFAD

4. Digitized road data - Road data produced with sufficient accuracy by digitization can be overlaid on the graphic display to create a simplified computer graphics equivalent of a map.

Because this study needs to compare aircraft in low flight against radar, infrared, and visual defenses, it is important to integrate terrain and forest for an accurate depiction of the flight path and an accurate calculation of intervisibility. The data preparation operations are made more difficult by the fact that DTED is an image raster format and DFAD is a polygon format, as shown in Fig. 1. STP proceeds by converting the DFAD to raster format and adding it to the DTED. The steps in this process are:

1. Convert the DTED data to an internal STP format (an image). Use image mosaicking if the study area covers parts of several DTED data sets.

2. Resample a subwindow of the DTED data to the selected pixel analysis size. For the Fulda Gap, the pixel size was 25 meters, making the 20 km x 20 km area an 800 x 800 image (20 km / .025 km).

3. Convert the DFAD contours to an internal STP format.

4. Perform an affine transform of the latitude-longitude values to the DTED coordinates using the corner points to define the transform.

5. Thin the DFAD contours by replacing nearly collinear lines by a single line using a tolerance of 25 meters.

6. Scribe the DFAD contours into an 800 x 800 image. The result, if viewed, would appear to be black lines outlining culture areas on a white background.

7. Fill each connected white area with a unique identifying number. A subsequent option in this step is to erase the boundaries, melting them at random into their neighbors.

8. A table of point identifications or seeds is built from the polygon file giving a coordinate and an associated fill number using the fill image to look up points just inside of each line. The polygon identifier from the DFAD file is placed in a column.

9. A voting procedure takes the majority vote of DFAD polygon identifiers for each fill number to associate fill numbers with DFAD identifiers.

10. The DFAD table is converted to an internal STP format keeping the DFAD identifier, the DFAD class code, and the height.

11. The two tables are joined using the DFAD identifier as a matching key. Residual areas are given the code for bare ground.

The intermediate product here is a DFAD fill image which registers to the DTED data, and a table that tells what each fill number is and how high it is. Next, the combined elevation image is produced:

12. The height values are injected into the fill image using the fill number column to look up what height goes into what pixel. The result is a culture height image.

13. To give the effect of random tree heights, the culture height image has the formula (.5 + .5 * rand) applied to each pixel, where each call of rand produces a pseudorandom number between zero and one. This formula can be changed as desired.

14. The DTED image is added to the randomized culture image to produce the combined elevation image.

Then, a display graphic (an equivalent of a map) is produced for use in the flight path planner program:

15. The DTED image is shaded by a simple algorithm that places the solar illumination in the southeast direction. Eight levels of shade are produced.

16. The DFAD table is divided into bare ground, trees, and all other classes. These are turned into the three color numbers for brown, green and purple, and are injected into the fill image using the same operation as step 12.

17. Using the STP image arithmetic module, the shade is combined with the three color map.

18. A contour algorithm is applied to the DTED elevation image to produce 50 meter elevation contours.

19. The contours are added to the color graphic image as white lines.

20. Roads are processed as in steps 4-6 and added to the color graphic image as black lines.

The HELCOM tables are not changed as a preparation step.

III. STP FLIGHT PATH GENERATION

The STP flight path generator (program FP) is used to input a high data resolution flight path over the prepared terrain and culture data sets, allowing the operator to control direction, elevation, and speed. The operator uses a keyboard to set numeric values and a mouse to locate each segment of the flight over the color graphic display. The flight path is checked by the HELCOM model so that it conforms to a realizable path. Two aspects of this control scheme need to be discussed.

First, the specifying of the elevation will cause only the end point of a flight segment to be set. HELCOM will fly a straight line between the points of that segment, and the actual elevation achieved along the segment will vary with the combined terrain and culture under the path (Fig. 2). For low flight, the straight line path will often intersect a hill or a tree (Fig. 3). In this case, the operator will see the "clobber" in a small magnifier window that is provided in the corner of the graphics screen. The operator has the choice of erasing the last segment (or last "n" segments) to retry a different path or allowing the clobber if it is deemed to be an allowable grazing of treetops. This latter situation occurs in a flight path that is simulating a weaving path at the level of the treetops.

Second, HELCOM operates by applying the tables of acceleration capabilities for the segment selected by the operator given the state of the aircraft at the start of the segment and the mode requested by the operator. The modes at present are accelerate, decelerate, fixed speed, dash, and pop-up. For example, if the aircraft is flying at 37 knots, is in the accelerate mode, and a near-level segment of 2100 ft is input, the HELCOM routine will apply the level flight maximum acceleration with a starting velocity of 37 knots and distance of 2100 ft, yielding a new final velocity. If peak velocity is reached along the way, the aircraft will fly the remainder at the peak velocity. At present, turn restrictions, overshoot, and undershoot are not implemented. However, examination of the flight paths in light of project requirements did not indicate a problem with these deficiencies.

The sequence of events in generating a flight path with FP is as follows:

1. Start the program and name the data sets to be input for the color graphic map, combined elevation, and sensor location. See Fig. 4 for the TAE screen used for input.
2. Display sensor patterns, if desired.

Side view

Magnifier

Map view
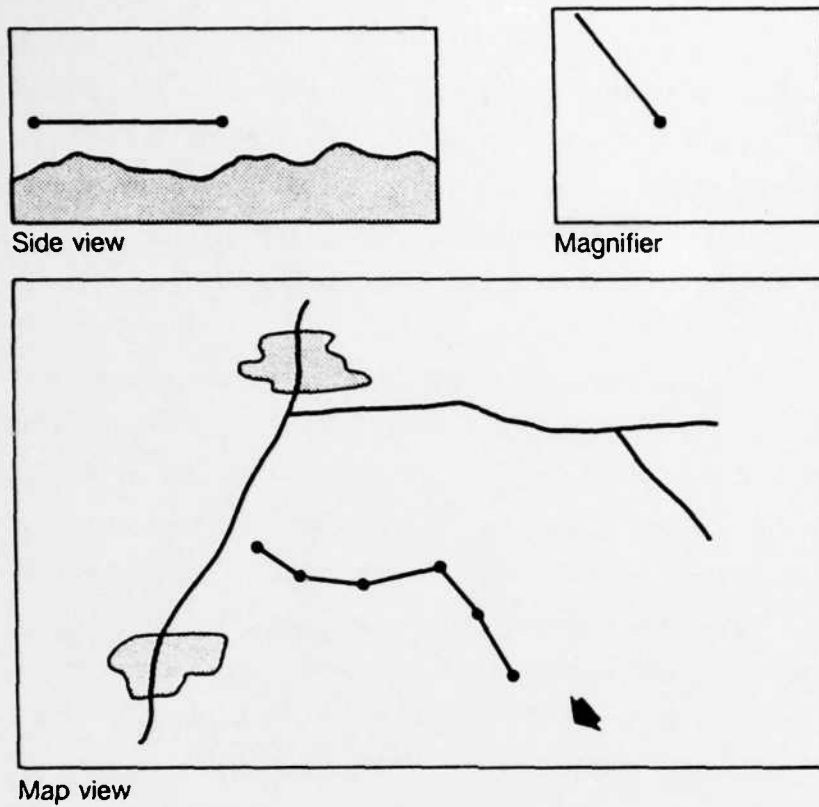
Fig. 2—Stepwise input of flight path

Trees

30   30
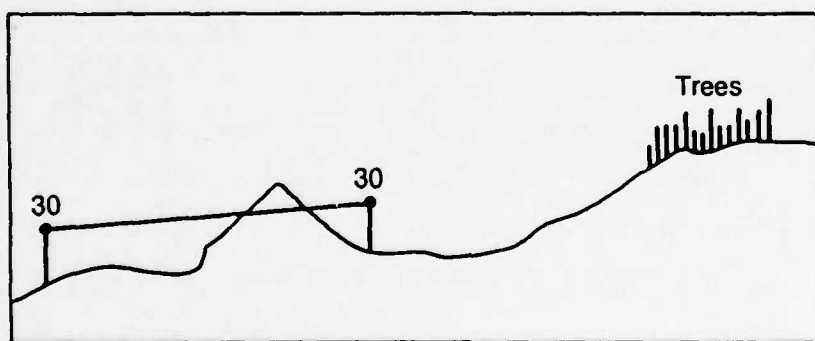
Fig. 3—Side view showing collision and trees

3. Display a previous path, if desired.

4. Select path entry option. Enter aircraft choice (presently LHX helicopter, AH-60, or LHX tilt rotor). Enter initial elevation above ground, general elevation of area above sea level, and maximum performance factor (Fig. 5).

5. With the mouse and cursor, select a starting location.

6. With the mouse and cursor, select the end of the first segment. Then view the segment as a black line on the map and as a red line in the terrain profile magnifier. If the segment is not wanted, it may be erased with the "e" on the keyboard. Repeated strokes of the "e" erase previous segments. Also view the status of the aircraft speed, elapsed time, aircraft and ground elevations, etc., in a side window of the graphics screen.

7. Step 6 may be repeated. If a change of mode is desired, the following keys are used: f - set fixed speed, d - decelerate, r - remove fixed speed, p - pop-up. The default mode is accelerate.

8. Select path save option. Enter a disk file name to hold the coordinate, time, velocity, and elevation information for the path.

The flight planner has evolved during 1988 to improve its operator interface. A demonstration of the current flight planner is given in the appendix.

- 14 -

current session saved to c

```
TAE TUTOR

TUTOR: proc "fp", library "/u/zobrist/utae"              [ Close ]
                        flight plan routine
[TAE-SAVRST] Your parameters have been restored from (lhx4fpx)

[Run] [Show...] [Initial] [Save...] [Restore...] [Structure] [Exit] [Tutor Help]

   PARM        DESCRIPTION                          VALUE

   in          graphic color input file            "/t/TERRAIN/zobrist/"

   in2         overflow for long filename          "lhx4color"

   dted        terrain input file with added       "/t/TERRAIN/zobrist/"
               culture height if desired

   dted2       overflow for long filename          "lhx4dted"

   radar       radar locations                     "lhx4radx"

   radar2      overflow for long filename          ""

   sline       input window starting line          0

   ssamp       input window starting sample        0

   nline       input window number of lines        800
               will be output size

   nsamp       input window number of samples      800
               will be output size

   latrange    lower and upper lat of data    (1) 50.443
               in degrees.fraction            (2) 50.621

   lonrange    lower and upper lon of data    (1) 9.69
               in degrees.fraction            (2) 9.974
```

Fig. 4—STP window for input of parameters and data sets

```
┌─────────────────────────────────────────────────────────────────────────┐
│ TAE TUTOR                                                                 │
├─────────────────────────────────────────────────────────────────────────┤
│ TUTOR: proc "fpdyn5", library "/u/zobrist/utae"            ┌────────┐     │
│                     initialize a helo flight path          │ Close  │     │
│                                                            └────────┘     │
│                                                                           │
├─────────────────────────────────────────────────────────────────────────┤
│ (Run) (Show...) (Initial) (Save...) (Restore...) (Structure) (Exit) (Help)│
├─────────────────────────────────────────────────────────────────────────┤
│     PARM       DESCRIPTION                              VALUE             │
├─────────────────────────────────────────────────────────────────────────┤
│ ⬍ helo_wch    1 - lhx30                                 2                 │
│               2 - apache                                                  │
│               3 - tiltrotor                                               │
│                                                                           │
│   helo_elv    helo skid elevation above                30                 │
│               ground in feet                                             │
│                                                                           │
│   helo_alt    ground elevation above                   2000              │
│               sea level in feet                                          │
│               only 2000 allowed for now                                  │
│                                                                           │
│ ⬍ helo_prf    helo max performance                     ▓▓▓▓              │
└─────────────────────────────────────────────────────────────────────────┘
```

Fig. 5—STP window for input of helicopter choice and initial settings

IV. STP FLIGHT PATH REFINEMENT AND INTERVISIBILITY ANALYSIS

The flight paths generated by the procedure outlined in Sec. III consist of the points input by the operator with a few additional points added by the HELCOM routine to indicate transitions from acceleration to steady or steady to deceleration. Typically, the operator inputs about 50 points for a 10 km flight path using 25 meter pixel resolution. This means that the points have an average spacing of about 200 meters (10 km / 50 points). The analysis procedures now applied to the paths can be set to a finer mesh to give an accurate portrayal of intervisibility from defensive sites and the resulting sequence of events. The combined elevation image is retained for a lookup of intervisibility at the finer mesh.

The flight path refinement and intervisibility analysis takes place in a large table that is handled by the data management modules of STP. The vertical ordering of records corresponds to the sequence of events in the flight path. A schematic of the table layout is shown in Fig. 6. The block labeled flight path contains the (x,y,z,t) of the flight path. This block is repeated for each sensor location. Other fields contain additional information such as ground elevation under the helicopter and derived information such as intervisibility of sensor to helicopter. The visibility windows are contiguous 1's in the latter column.

The path refinement phase uses the following steps:

1. A table of defensive site locations in latitude-longitude and feet above ground is read into a small table.

2. Additional fields containing UTM coordinates are calculated.

3. Ground elevation is obtained from the combined elevation image (remember that trees have been cleared from these spots in the data preparation phase).

4. Defensive site elevation above sea level is calculated by adding the ground height and sensor height.

5. The aircraft flight path is interpolated with additional points by adding uniformly spaced time values in the time column that correspond to a maximum distance between points selected by the operator (typically 25 meters).

6. The velocity for added points is interpolated according to the time column. Time increments are put into a new column. Distance increments are calculated as velocity times the time increment. A running sum is taken of the distance increments. The map coordinates for added points are interpolated according to the running sum of distance. This entire calculation gives an accurate position and time of the end points

of accelerations and decelerations assuming uniform acceleration. It is off only slightly for the actual case of nonuniform acceleration-deceleration, but this is acceptable since the operator input points are strictly as given by HELCOM. A helicopter path sequence number is added.

7. Additional fields containing UTM coordinates of the flight path are calculated.

8. The ground elevations at the helicopter path points are looked up in the combined elevation image. At the user input points, the helicopter elevation above sea level is calculated. The sea level elevation is then linearly interpolated according to the time column. The actual helicopter elevation is then calculated as the difference between the elevation above sea level of the helicopter and the elevation of the ground above sea level.

Fig. 6—Table layout for intervisibility analysis

9.   For analysis purposes, the average elevation of the helicopter over the entire path with respect to time is calculated.

10. The defensive site location and the helicopter path table are joined by cross-product. A very large table results, with the helicopter path repeated for each defensive site (Fig. 6). Each line of the table has a single pair — one defensive site location and one helicopter location. About 30 fields of information are available including UTM location, time, elevations, velocity, etc.

11. The PPLOS (point-to-point line of sight) program is applied to the table and the combined elevation image to provide a new column that contains a zero for not visible and a one for visible according to interposing terrain, trees, or buildings and including the effect of the earth's curvature. The program is based on image processing techniques that allow it to operate quickly with very large elevation images and very large tables of intervisibility points. The image here was 800 x 800, but 10000 x 10000 can be handled. The Bresenham algorithm (Ref. 3) is used to step from the helicopter point to the defensive site in the pixels of the elevation image. The image is read in consecutive swaths that fill the working memory of the SUN computer without paging. Then all of the point pairs are stepped through the current swath of data.

The procedure above yields a table that can be used for analysis of the line-of-sight windows (in time and space) presented by a helicopter path to a set of defensive sites or for a more detailed analysis of particular defensive weapon types. The procedure for aggregating the windows is as follows:

1.   Subtract UTM coordinates in north and east directions and calculate the hypotenuse to get line of sight distance.

2.   For contiguous zeros or ones in the visibility column, make a running sum of the time increments.

3.   Aggregate and collapse the table using the visibility column as a control and the defense identification as a secondary control. Thus, for each break in the control values, a new group of records is defined and collapsed into one record. A maximum control field is also defined for the running sum of time defined in step 2. The values kept in the resulting record are picked from the same input record that had the maximum running sum.

The result is a small file with one record for each window of geometric visibility or nonvisibility. The length of the window in seconds is given, and its distance from the defensive site is also given. The procedure saves these data in a systematic fashion for further processing. As each case is run, a three letter code may be input by the operator for flights and for defensive site data sets. The three letter code is used to name a new large table for the collection of all window records. Separate files can also be kept with filenames that are automatically generated by the three letter code and other parameters of the case.

V. STP WINDOW ANALYSIS TECHNIQUES

The large collected file produced by the intervisibility algorithms is used for a series of steps that analyze the geometric exposure of the aircraft. The file contains a field called nominal velocity that is set to the desired velocity for fixed velocity runs. For these, the helicopter will fly at the desired velocity except for the initial accelerate, the final decelerate, and steep hill climbs that forbid the desired speed. For variable speed runs, the nominal velocity is set to zero. There are slight variations in the analysis below for the two types of velocity settings. The procedure begins by selecting the subset of windows for the desired analysis.

1. Retrieve all windows that are visible (deleting the nonvisible).
2. Optionally, retrieve windows that are classified as being over flat or over hilly terrain. This classification procedure uses an image processing operation to determine flat or hilly and point lookup to fill the field to be used for retrieval.

The result is a base file for statistics and plotting which is copied for each of the steps below.

3. Sort the base file by aircraft and nominal velocity. Set up a column containing all ones. Then aggregate and collapse the file by these fields summing the other fields. The column of ones becomes a count of windows for each aircraft type and nominal speed. For variable speed cases, the actual velocity is used in place of the nominal velocity with rounding to the nearest 5 knots value (a procedure hereafter known as "bucketing"). These statistics are then reported and plotted.
4. Bucket the window lengths. Process the file as in step 3 except add window length buckets to the two sort fields. The result will be a histogram of window lengths by aircraft and velocity.
5. Sort the base file by aircraft, path number, and nominal velocity. Aggregate and collapse the file by these fields. The average elevation of the paths can then be reported.
6. A measure of the lethality of a window can be defined as length of the window in seconds divided by the distance of the window from the defense site in km. These values are then bucketed. Step 4 is repeated using lethality instead of window length.

7. A more advanced measure of the lethality of the window is based on deriving for a window the number of kill opportunities of a generic missile defense weapon. Assume that the generic weapon has a detection, acquisition, and firing sequence delay of t_g and a missile flyout velocity of v_g. Also, assume that the next sequence commences at the moment the missile hits the aircraft. These assumptions downgrade distant windows because the flyout time is longer, and they upgrade long windows because one or more complete sequences can fit in them. They are also calculated based on the defense locations given in the study case. This new lethality metric is then bucketed and treated as in step 6 or step 4.

VI. STP ATTRITION MODEL

The STP Attrition Model was developed to analyze the survivability of the LHX
SCAT (aerial scout-attack), AH-64, and LHX tilt rotor aircraft against the ZSUX, SA-13,
SA-14, and SA-15 air defense systems under a variety of missions.

The unaggregated table created in Sec. IV, steps 1 to 11, from a mission flight path
flown over micro-terrain is used as input to the STP Attrition Model. Each entry in the table
has the simulation time, the aircraft coordinates, the defensive site coordinates, and a
visibility field. The choice of an air defense system is an input to the model. The final
output of the model is an attrition rate L for a particular mission flight path that is then used
to calculate Poisson statistics.

A low speed (60 knots) and a high speed (120-180 knots) head, tail, flank, and bottom
radar cross section or infrared signature for each aircraft/air defense combination are inputs
to processing the variable speed flight path through the detection algorithm. For hits and
kills the data required for each weapon system include missile velocity, and the target and
vulnerable areas (head, tail, flank, top, and bottom) of the aircraft against the weapon
system. If a proximity kill weapon system is under consideration, the circular error probable
and number of shots are also needed. The data input to the model were extracted from
Army Materiel Systems Analysis Agency (AMSAA) data.

The STP Attrition Model algorithm can be broken down into six major steps: STP
flight path refinement, calculation of break lock-on probability, calculation of detection
probability, calculation of hit probability, calculation of kill probability, and generation of
statistics. A more detailed description follows.

1. As described in previous sections, interactively generate the candidate flight paths
    using the flight planner. The flight path generated incorporates the aircraft flight
    dynamics and terrain to minimize exposure to threat weapons. Execute STP flight path
    refinement procedure to obtain instances of clear line of sight (CLOS) between the
    aircraft and threat site.
2. Obtain break lock-on probability. The time duration under a visibility window is used
    as an index into a table of break lock-on probabilities.
3. Calculate detection probability for each LOS window. First determine the direction
    and position of the target with respect to the sensor. Calculate sensor coordinates in
    new coordinate system (L, M, N) from coordinates (x, y, z). Select the appropriate

radar cross section or infrared signature based on weapon system and aircraft velocity. The following substeps calculate a composite signature based on the type of sensor used in the weapon system. If the weapon system uses a radar sensor (ZSUX, SA-15), then the following substeps are followed. Given the radar cross sections of the target for normal and Doppler radar, calculate the radar cross section constants based on the spatial orientation of the target to the radar. Use the constants to solve for the signal-to-noise and signal-to-clutter values for both normal and Doppler radar and choose the best signal. Otherwise the weapon system uses an infrared sensor (SA-13, SA-14). Given the infrared signatures of the target, calculate the infrared signal-to-noise ratio based on the spatial orientation of the target to the sensor. The resulting radar or infrared signal is then used as an index into a table of detection probabilities.

4. Calculate hit probability. Eliminate the LOS windows that do not have at least one entry that meets the detection threshold. For each remaining LOS window, take the earliest time of detection offset by the missile firing sequence to obtain time of missile fire. Match up missile flyout time — the range between target and sensor divided by missile velocity — against the length of time visible since detection and register a hit if the missile arrives at the target within the LOS window.

5. Calculate kill probability. For each visibility window, take the earliest time a hit is registered. Based on projected target areas, projected vulnerable areas, the spatial orientation of the target, and whether the weapon system uses a direct or proximity missile, calculate the kill given hit probability.

6. Calculate the aircraft attrition rate for the mission. For each aircraft, compute an attrition metric from individual kill probabilities and convert probabilities to a Poisson measure of the attrition rate for the flight path.

VII. FUTURE DEVELOPMENT

The LHX project has fostered the development of a complex set of interrelated tools (the STP or SUN Terrain Procedures) to analyze aircraft flight over terrain with defenses. An effort to generalize this work for multiple project use and the support of models in addition to JANUS is now under way. The three most fundamental categories of tools are: geographic information systems, interactive graphics, and analysis procedures. Fig. 7 shows how these categories of tools will provide multiple project support from a single software base system. The new software system is called Cartographic Analysis and Geographic Information System (CAGIS). Cost savings and increased capability will derive from the following:

1. The CAGIS system contains general purpose program modules that are reused in many projects.
2. The CAGIS modules are under change control in a system library, hence are more reliable than custom software.
3. The custom analysis procedures are analyst-written procedures using CAGIS modules.
4. Custom graphics programming (which is notoriously difficult) is reduced in difficulty by the supporting CAGIS and analysis capabilities.
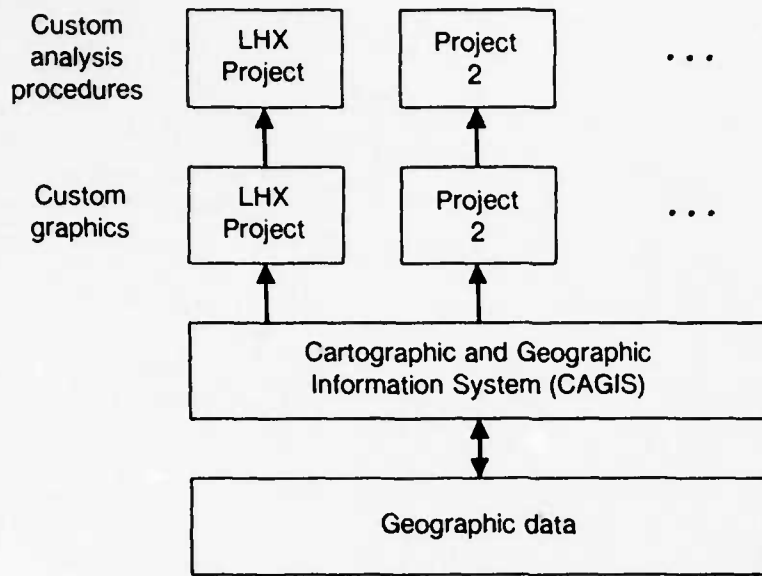
Fig. 7—Multiple project support with CAGIS

Appendix
A FLIGHT PLANNER DEMONSTRATION

This interactive demonstration uses a modernized version of the software used in the LHX project. The following instructions detail the setup actions and the many "point-push" actions to manipulate the image, paths, and patterns. **MOVE** is short for move the mouse, **RIGHT** is short for press the right side button on the mouse. Similarly, **MIDDLE** and **LEFT** are button actions. **SELECT** is short for while holding the button down move the mouse until the screen arrow is within the area of the labelled screen menu selected and release the button. **SHIFT** is short for press the shift key on the keyboard. Logon on a **Color SUN Workstation**. Then change directory by:

cd /s/app/app

If suntools windows appear automatically, exit the suntools and reenter suntools as follows:

suntools -s .suntools

To setup the CAGIS commands, enter:

source log

To run the demonstration type:

cagis

Wait until the **CAGIS** prompt appears (about 30 seconds). Proceed to the next page and demonstrate the various Flight Planner actions. When the demonstration is complete, proceed with the following actions to exit the Flight Planner. To remove a window:

MOVE to the banner at the top of the window and **RIGHT** and **SELECT Done**.

The window will disappear. When all the windows have disappeared the cursor returns to the CAGIS prompt. Then type:

exit

To quit the Flight Planner demonstration:

MOVE to the image window and **RIGHT**.

A pop-up menu will appear.

SELECT quit.

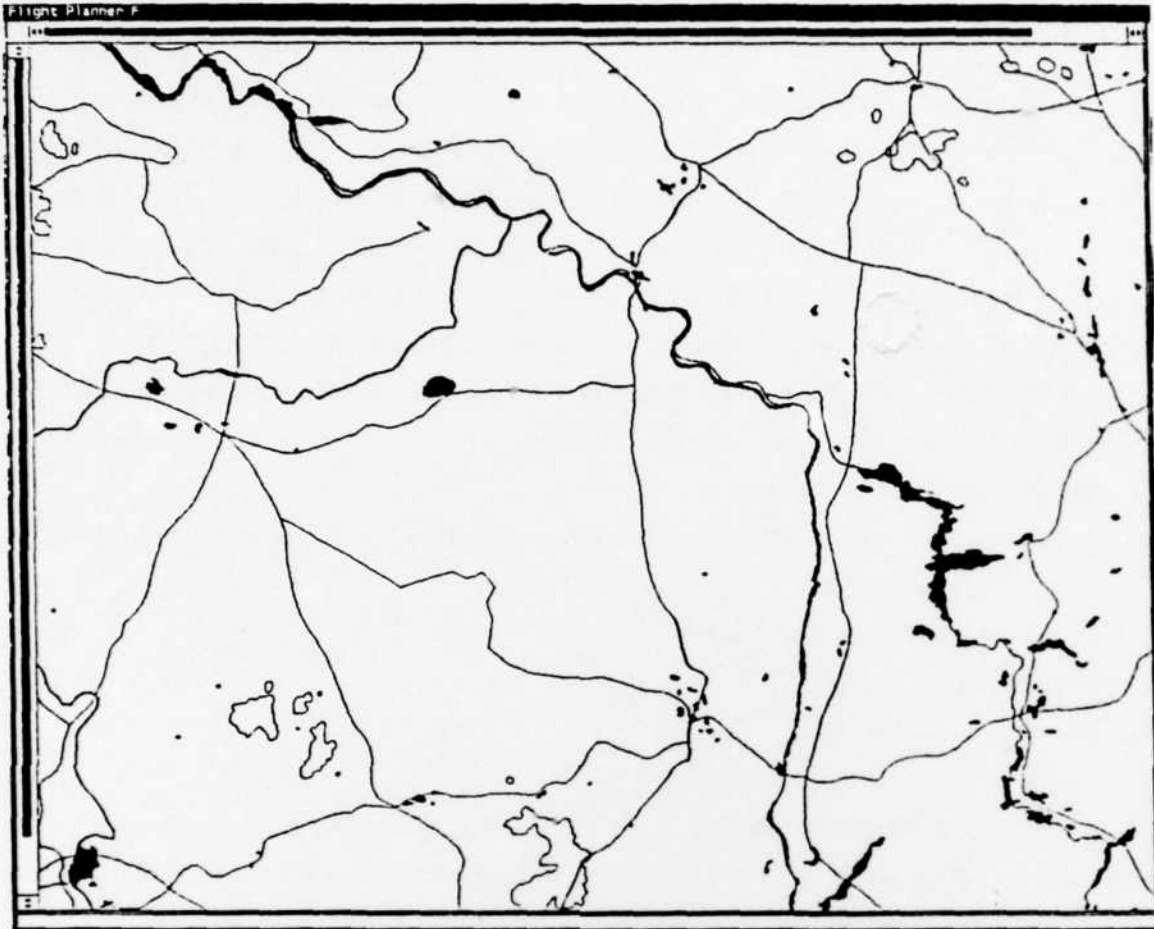All windows will disappear and CAGIS will exit.

Fig. A.1—Flight Planner image window (normally in color)

Running the Flight Planner Demo

At the **CAGIS** prompt type:

t ffp

The Flight Plan Routine window will appear. Now take the following actions:

MOVE to **RESTORE** and **LEFT**.

The Restore Tutor Parameters window will appear, then

MOVE to **Parameter File Name** and type: **ffp MOVE** to **OK** and **LEFT**.

The Flight Plan Routine window will fill with parameters and **BEEP**.

MOVE to **RUN** and **LEFT**.

Next the Flight Path Parameters window will appear.

MOVE to **RESTORE** and **LEFT**.

The Restore Tutor Parameters window will appear, then

    MOVE to **Parameter File Name** and type: **fdy MOVE** to **OK** and **LEFT**.

The Flight Path Parameters window will fill with parameters and **BEEP**.

    MOVE to **RUN** and **LEFT**.

The Flight Path Parameters window will disappear and a large image window will appear. After about 30 seconds a small black rectangle will appear in the upper left corner. It will slowly, line-by-line, turn white. This will take several minutes. When this process is complete the entire image window will fill with the terrain data in color including forest, rivers cities, boundaries, etc. See Fig. A.1.
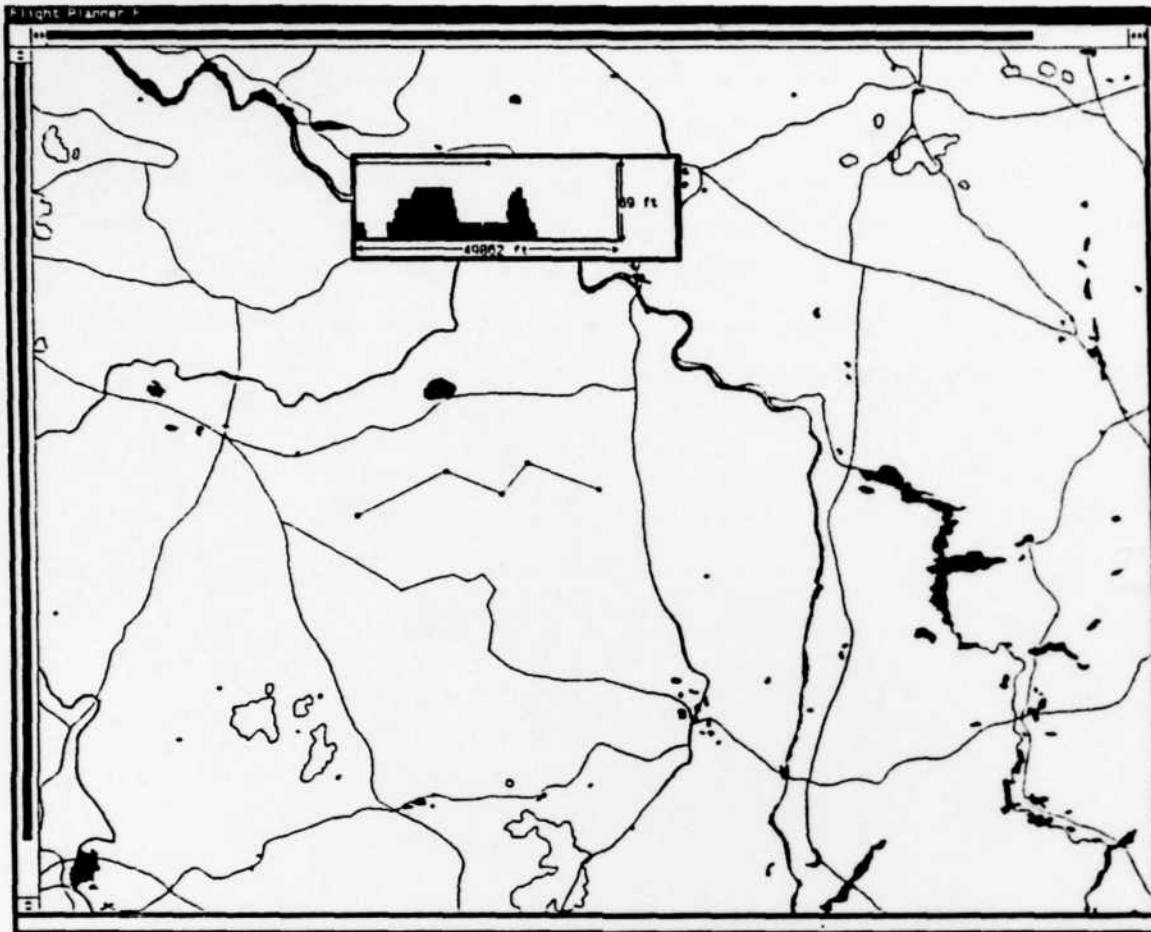
Fig. A.2—Plotting of a flight path (with side view)

Plotting a Flight Path

To create a path across the terrain in the image window, take the following actions:

MOVE to the image window and **RIGHT**.

A pop-up menu will appear.

SELECT Edit Path and **MOVE** to the arrow on the line following **Edit Path**.

A second menu will pop-up.

SELECT New Path.

You are now in the path creation mode. To create a flight path:

MOVE to any point you choose and **LEFT**.

A flight path point will be drawn.

Then **MOVE** to any second point and **LEFT** again.

A second point will be drawn and a side-view window will appear showing the flight altitude and the terrain traversed. See Fig. A.2. Repeat this action until the flight path is complete.

MOVE to the image window and **LEFT** and **SELECT Path** and **MOVE** to the arrow on the line following **Path** and **SELECT Save Path** in the second pop-up menu.

The Pathtools Dynamic Parameters window will appear.

Enter the filename for the path and **MOVE** to **RUN** and **LEFT**.

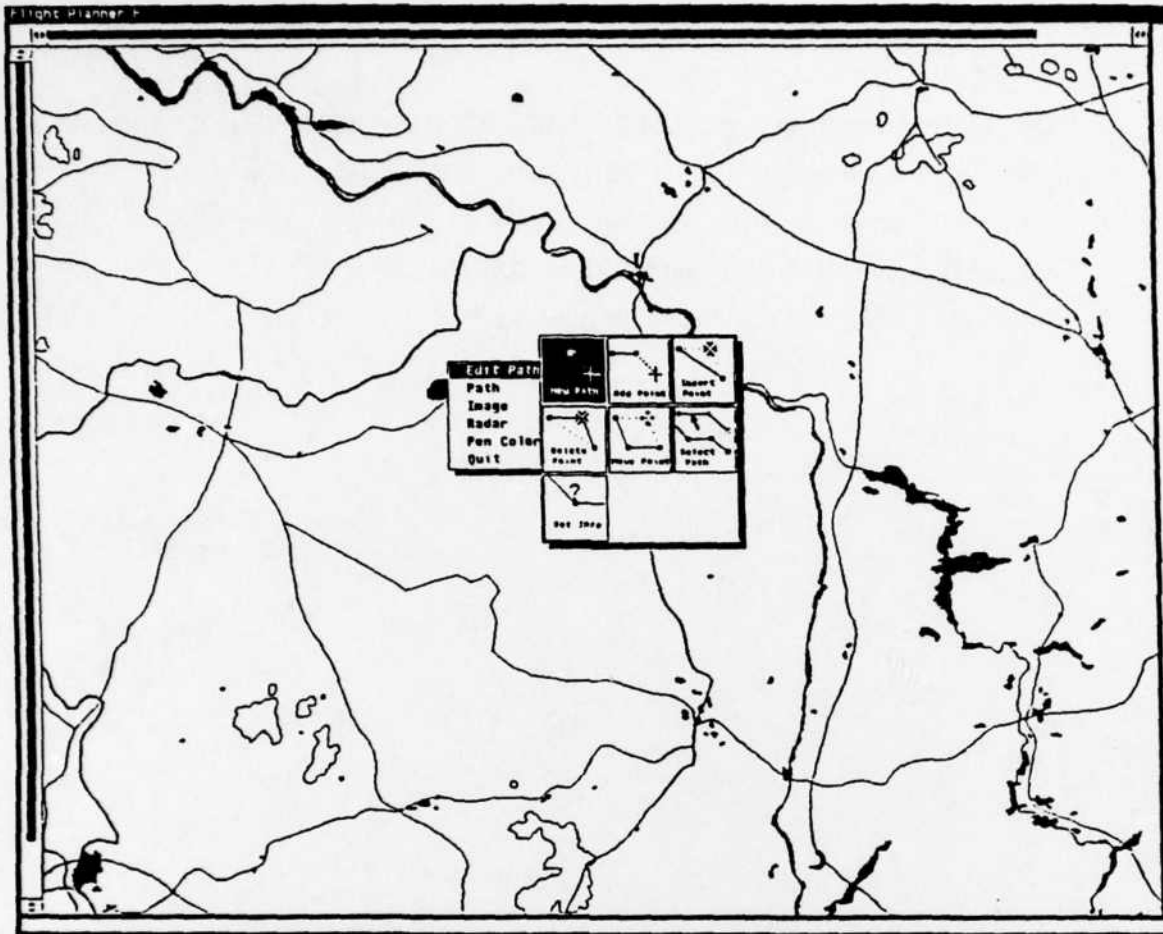This will save the flight path parameters for future uses.

Fig. A.3—Flight path creation menu

Flight Path Creation

To modify a flight path:

MOVE to the image window and RIGHT.

A pop-up menu will appear.

SELECT Edit Path and MOVE to the arrow on the line following Edit Path.

The a second menu will pop-up.

SELECT the command you want.

Your choices are (see Fig. A.3):

New Path to begin a new path.

Add Point to add more points to a path.

Insert Point to place a point between two points.

Delete Point to remove a point.

Move Point to hook a point and move it.

Select Path to change paths.

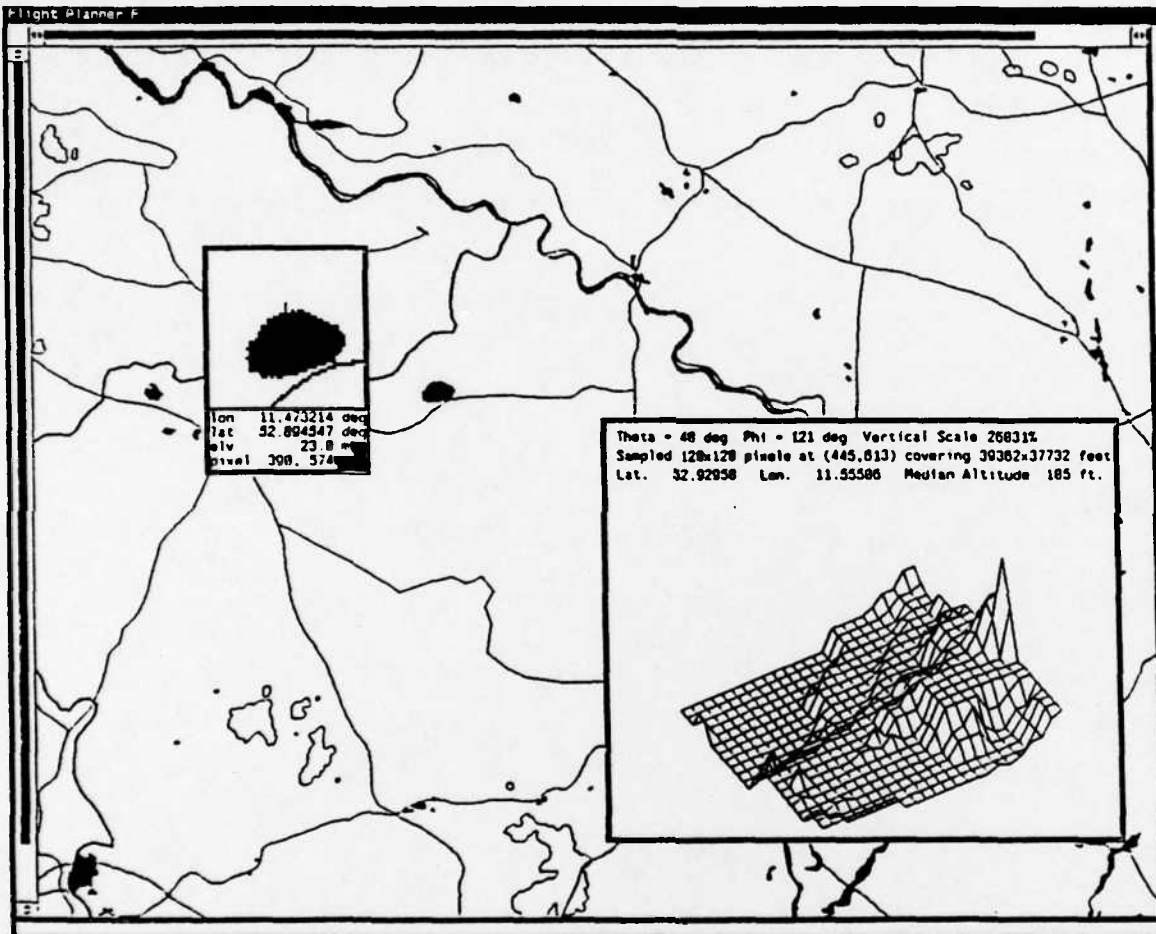**Get Info** to provide more information about a point.

Fig. A.4—Flight Planner magnifier and wire diagram

Flight Planner Magnifier

To magnify the any location (by three times magnification):

MIDDLE to magnify the current point.

Additional information is displayed beneath the magnified image

To create a wire diagram window (three dimensional) for the terrain about a point:

SHIFT and **MIDDLE** at the current point.

To change the wire diagram window:

RIGHT within the wire diagram window for a pop-up menu of changes.

To change the color of a path:

RIGHT on any point and **SELECT Pen Color**. **SELECT** color.

To change the image shading:

SHIFT and the letter **s**

The shading of the image will alternate with the light coming from either the upper left or the lower right.

SHIFT and the letter **g**

The shading of the image will alternate with gray or normal coloring. See Fig. A.4.
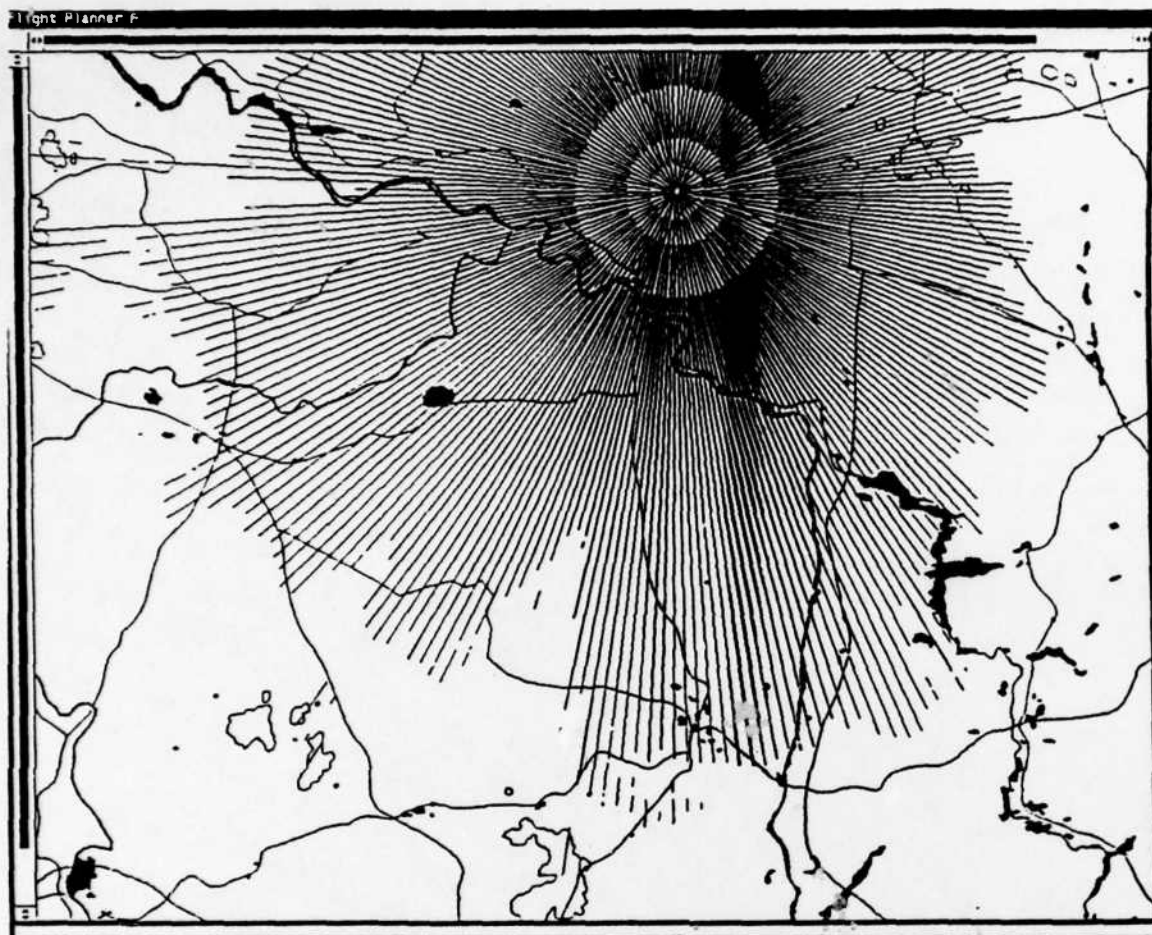
Fig. A.5—Flight Planner radar pattern generation

Flight Planner Radar Pattern Generation

To plot a radar pattern from a previously chosen radar:

MOVE to the image window and **RIGHT**.

A pop-up menu will appear.

SELECT Radar and **MOVE** to the arrow on the **Radar** line.

A second menu will pop-up.

SELECT Load Radar Pattern.

A radar pattern window will appear:

MOVE to **RESTORE** and **LEFT**.

The Restore Tutor Parameters window will appear, then

MOVE to **Parameter File Name** and type: frp **MOVE** to **OK** and **LEFT**.

The radar pattern window will fill with parameters and **BEEP**. **MOVE** to **RUN** and **LEFT**.

See Fig. A.5.

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